Deep Inelastic Lepton Scattering With Polarized Nucleons

- Extension of the event generator DJANGOH by the option of target polarization -

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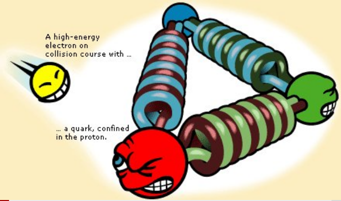

Overview

1. Motivation
   - Why the interest in spin polarized targets?
   - Why the need for an event generator?
2. Event generator DJANGOH
3. Deep inelastic lepton hadron scattering
   - Born level
   - Leptonic $\mathcal{O}(\alpha)$ corrections
   - $\mathcal{O}(\alpha)$ corrections on the quark line
   - Charged Current
4. Conclusion & outlook

- experiments with polarized nucleons allow extraction of spin dependent structure functions/PDFs

EMC: "Proton Spin Crisis"

Sum of the spins and orbital momenta of the quarks in the proton complies only with ≈ 30% of the total proton's spin
Can the "missing spin" be linked to the gluons?
$1/2 = \Delta S/2 + \Delta G + L_q + L_g$

- Measurement of scaling behaviour of the structure function $\frac{\partial g_1(x,Q^2)}{\partial \log Q^2}$ allows for example to draw conclusions about the spin dependent gluon distribution
- event generator DJANGOH without target polarization so far!

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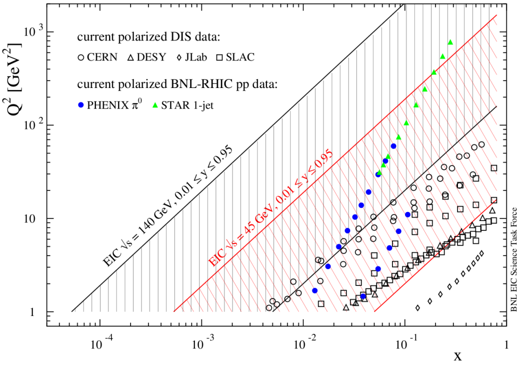
- new electron-ion-collider experiments with spin polarization are in the process of planning (eRHIC [BNL], LHeC[CERN], ELIC[JLab])
- achievable parameter range will be expanded
- more precision needed

⇒ effects of higher orders have to be taken into account



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⇒ optimization of the measurement conditions and comparison of theory and experiment

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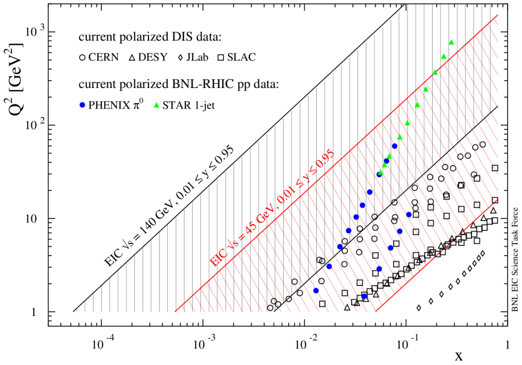

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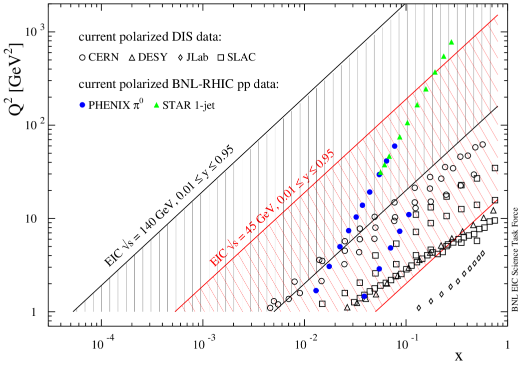

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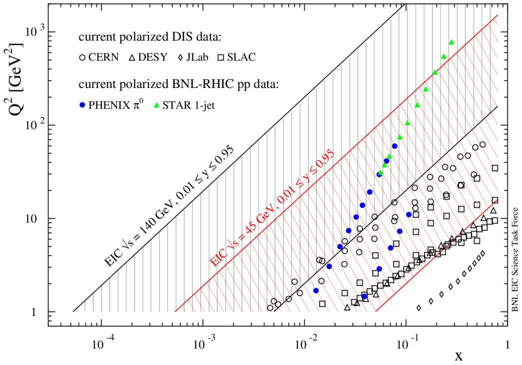

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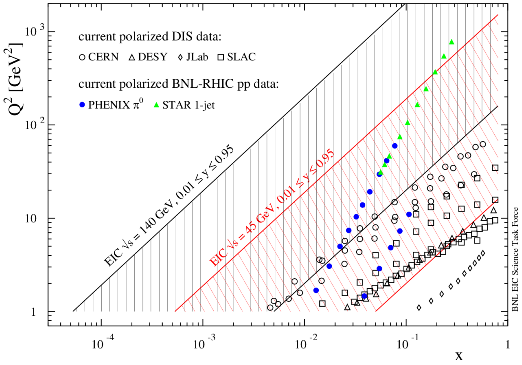

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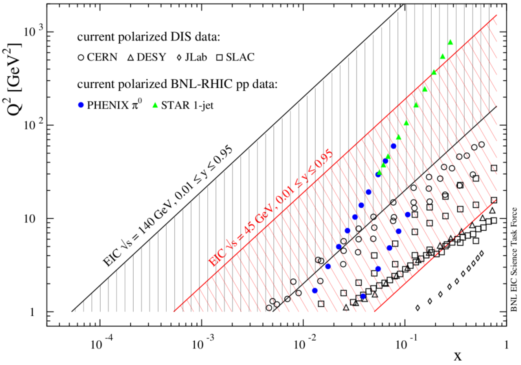

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Overview

- eventgenerator for deep inelastic lepton hadron scattering
- written in Fortran77 by Hubert Spiesberger in the time from 1996 till 2005 for HERA
- contains Monte Carlo program HERACLES and an interface to LEPTO
- original version is able to generate events for DIS of longitudinal polarized leptons off unpolarized hadrons (with or without QED corrections)
- reconstruction of the hadronic final state by fragmentation with PYTHIA/JETSET and/or parton cascades with ARIADNE
- complete cross section is integrated with the Monte Carlo algorithm VEGAS to be used as an relative weight for event generation
- events and parameters are written to an output file and a user routine fills histograms with respect to different kinematic variables

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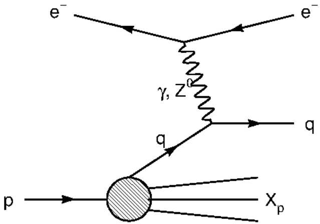
Charged current



neutral current: γ-/Z-exchange

$$\mathcal{M}^i \propto \overline{u}_\ell(k', s'_\ell)\Gamma_\ell^{i\,\mu} u_\ell(k, s_\ell)\overline{u}_\mathrm{q}(p', s'_\mathrm{q})\Gamma^i_{\mathrm{q}_\mu} u_\mathrm{q}(p, s_\mathrm{q})$$

with $\Gamma_f^{i\,\mu} = (v_f^i + a_f^i\gamma_5)\gamma^\mu$ for $i = \gamma, \gamma Z, Z$; $f = \ell, \mathrm{q}$

$$\sigma_{\mathrm{e^-p \to e^-}X_P} \propto \sum_\mathrm{q} \sum_{h=\Uparrow\uparrow,\Uparrow\downarrow} \int d\xi\, dQ^2\, d\sigma_{\mathrm{e^-q\to e^-q}}\, f_\mathrm{q}^h(\xi, Q^2)$$

with PDFs $f_\mathrm{q}^h(x) \mathrel{\widehat{=}}$ probability to find a quark of flavours q with share of momentum x and helicity h parallel ($\Uparrow\uparrow=\Downarrow\downarrow$) or anti parallel ($\Uparrow\downarrow=\Downarrow\uparrow$) to the polarization of the proton

(hereafter: terms $\mathcal{O}(m_\ell^2/Q^2)$ und $\mathcal{O}(M_\mathrm{p}^2/Q^2)$ neglected)

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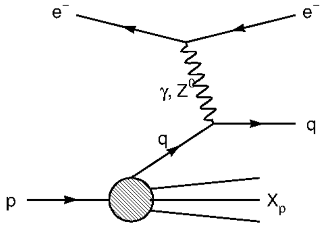

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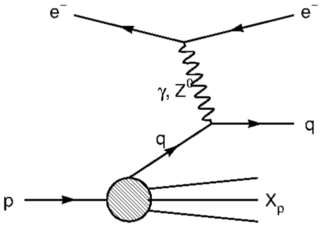

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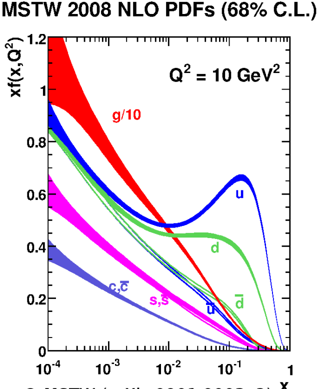
spin averaged PDFs:

$$q(x, Q^2) = \frac{1}{2}\left[f_q^{\Uparrow\uparrow}(x, Q^2) + f_q^{\Uparrow\downarrow}(x, Q^2)\right]$$



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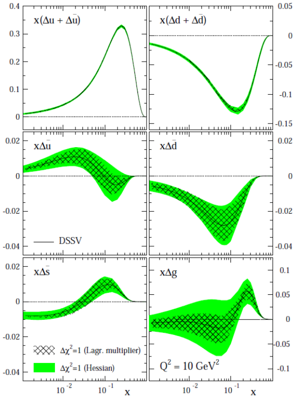
spin dependent PDFs:

$$\Delta q(x, Q^2) = \frac{1}{2}\left[f_q^{\Uparrow\uparrow}(x, Q^2) - f_q^{\Uparrow\downarrow}(x, Q^2)\right]$$



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$$\sigma_{e^-p\to e^-X_P} \propto \sum_q \int d\xi dQ^2 \left[d\sigma^{\text{unpol}}_{e^-q\to e^-q}\, q(\xi, Q^2) + H d\sigma^{\text{pol}}_{e^-q\to e^-q}\, \Delta q(\xi, Q^2)\right]$$

with degree of proton polarization H

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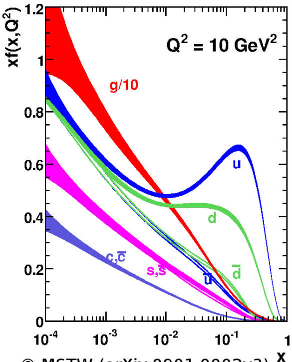

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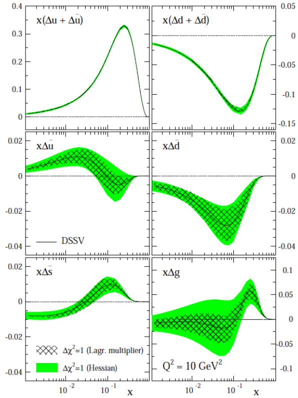

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Structure functions

differential cross section $\left(D^{\gamma} = 1,\ D^{\gamma Z} = \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha} \frac{Q^2}{Q^2+M_Z^2},\ D^Z = \left(D^{\gamma Z}\right)^2 \right)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{\pi\alpha^2}{2xyQ^2} \sum_{i=\gamma,\gamma Z,Z} D^i \left[xF_1^i\left(x,Q^2\right) Y_+ + xF_3^i\left(x,Q^2\right) Y_- \right.$$
$$\left. - H \left[xG_3^i\left(x,Q^2\right) Y_+ + xG_1^i\left(x,Q^2\right) Y_- \right] \right]$$

$x = Q^2/(2P\cdot q)$, $y = (P\cdot q)/(P\cdot k)$, $Y_\pm = 1 \pm (1-y)^2$

with the structure functions:

$$F_1^i \propto \left[\mathrm{q}\left(x,Q^2\right) + \bar{\mathrm{q}}\left(x,Q^2\right) \right] \qquad G_1^i \propto \left[\Delta\mathrm{q}\left(x,Q^2\right) + \Delta\bar{\mathrm{q}}\left(x,Q^2\right) \right]$$
$$F_3^i \propto \left[\mathrm{q}\left(x,Q^2\right) - \bar{\mathrm{q}}\left(x,Q^2\right) \right] \qquad G_3^i \propto \left[\Delta\mathrm{q}\left(x,Q^2\right) - \Delta\bar{\mathrm{q}}\left(x,Q^2\right) \right]$$

Measurement of structure functions

spin independent structure functions F_1^i, F_3^i accessible by scattering off unpolarized target

e.g., for small values of x, Q^2 (Z-exchange suppressed, $F_3^\gamma = 0$)

$$\frac{d^2\sigma^{H=0}}{dx\,dy} = \frac{d^2\sigma^{\mathrm{unpol}}}{dx\,dy} \propto F_1^\gamma\left(x, Q^2\right)$$

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$$A_{\mathrm{par}} = \frac{d^2\sigma^{H=-1} - d^2\sigma^{H=1}}{d^2\sigma^{H=0}} = \frac{d^2\sigma^{\mathrm{pol}}}{d^2\sigma^{\mathrm{unpol}}} \propto \frac{G_1^\gamma\left(x, Q^2\right)}{F_1^\gamma\left(x, Q^2\right)}$$

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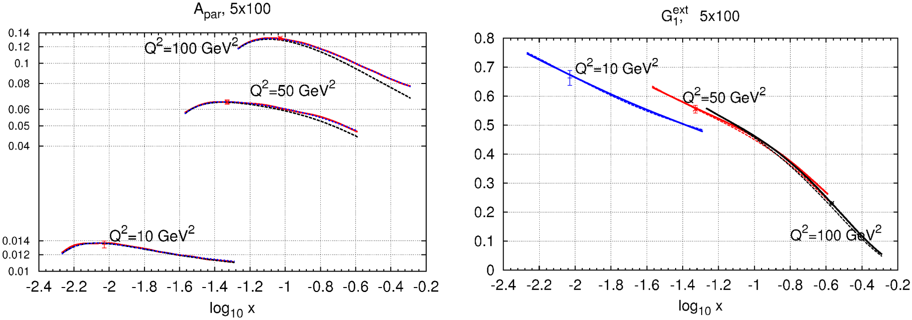
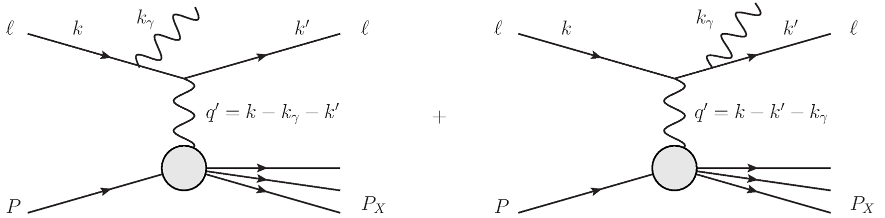
Pseudo data generated with DJANGOH

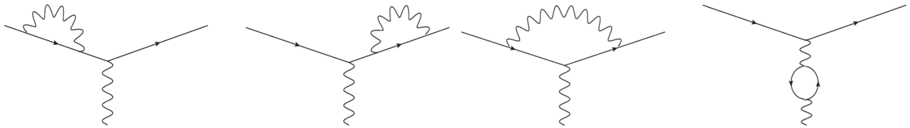


bremsstrahlung (initial and final state)



if not detected: $\frac{d^2\sigma}{dx\,dy} \propto \int \frac{d^3 k_\gamma}{2\omega(2\pi)^3} \frac{d^5\sigma_{\mathrm{bs}}}{dx\,dy\,d^3k_\gamma}$ (divergent!)

virtual corrections



corrections to the vector- and axial couplings v_ℓ, a_ℓ and multiplicative factors (divergent!)

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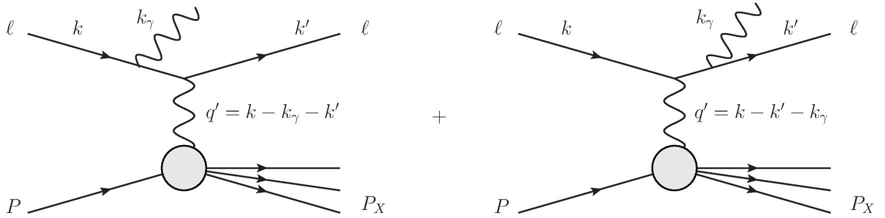

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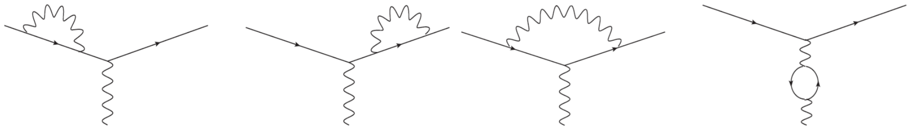

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$$-H\left[xG_3^i\left(x,Q^2\right)Y_+^{\mathrm{bs}} + xG_1^i\left(x,Q^2\right)Y_-^{\mathrm{bs}}\right]$$

with more complicated functions Y_+^{bs} and Y_-^{bs} (already available in DJANGOH)

divergences in Y_+^{bs} and Y_-^{bs} $\rightarrow$ radiative channels

$\propto (k \cdot k_\gamma)^{-1}$	initial state
$\propto (k' \cdot k_\gamma)^{-1}$	final state
$\propto Q^{-2}$	Compton

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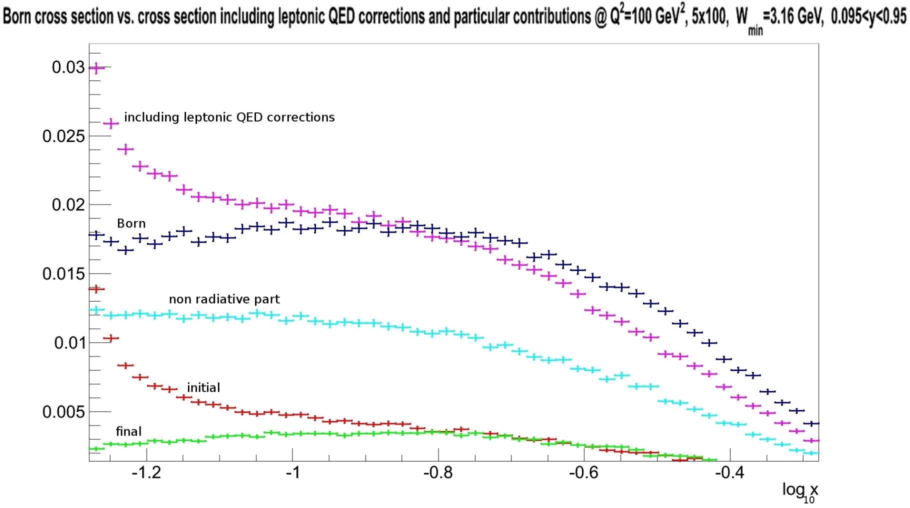
bremsstrahlung+virtual corrections (Kinoshita-Lee-Nauenberg: free of divergences)

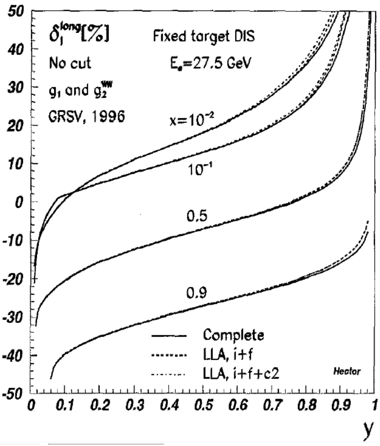
$$\sigma_{\mathrm{rc}_\ell} = \sigma_{\mathrm{nR}_\ell} + \sigma_{\mathrm{bs}_\ell} = (1 + \delta_{\mathrm{v}_\ell} + \delta_{\mathrm{s}_\ell})\sigma_{\mathrm{B}} + \sigma_{\mathrm{i}_\ell} + \sigma_{\mathrm{f}_\ell} + \sigma_{\mathrm{C}_\ell}$$

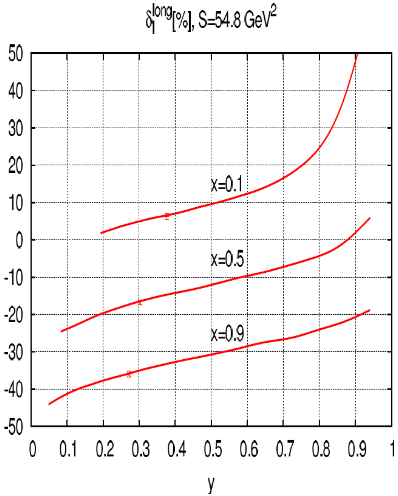


test: qualitative comparison with Bardin et al.

$$\delta_\ell^{\rm long} = \frac{d^2\sigma^{\rm pol}_{{\rm rc}_\ell} - d^2\sigma^{\rm pol}_{\rm B}}{d^2\sigma^{\rm pol}_{\rm B}} \times 100\%$$

D. Bardin et al./Nuclear Physics B 506 (1997) 295–328

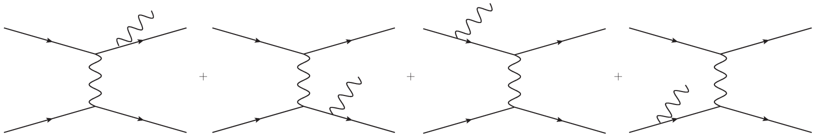




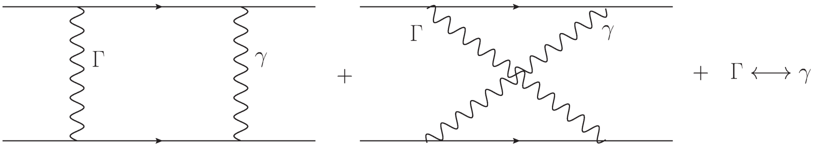
quark bremsstrahlung and virtual corrections to the quark vertex

- analogous to deliberations in the leptonic case ($\ell \leftrightarrow \mathrm{q}$)!
- sum free of divergences (collinear divergences regarding initial state can be absorbed in redefined PDFs)

interference of leptonic and quark bremsstrahlung (divergent!)



box diagrams (compensate divergences in lepton-quark-interferenz)



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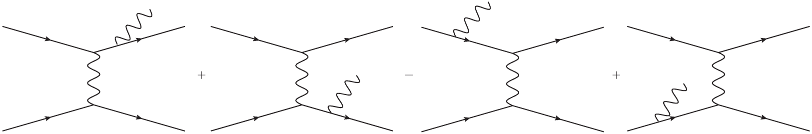

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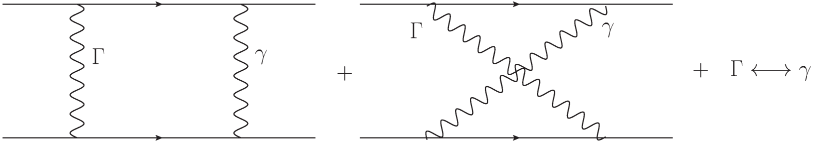

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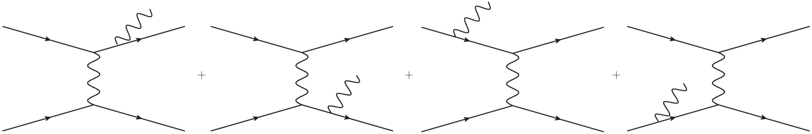

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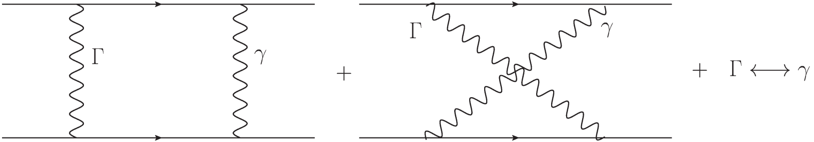
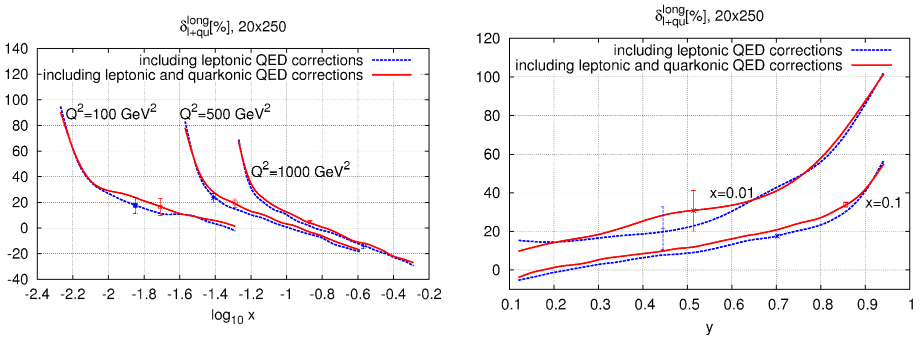


influence of QED quark corrections $\delta^{\text{long}}_{\ell+q} = \frac{d^2\sigma^{\text{pol}}_{\text{rc}_{\ell+q}} - d^2\sigma^{\text{pol}}_{\text{B}}}{d^2\sigma^{\text{pol}}_{\text{B}}} \times 100\%$




```
DJANGOH 4.7.0a FOR eRHIC FOR P, NLO at 20x250, X=0.1, Wmin=3.16, 0.095<Y<0.95
 CROSS SECTIONS ACTUALLY APPLIED FOR SAMPLING (IN NANOBARN):
 TOTAL CROSS SECTION,  SIGTOT =             4.6819E+00 +/- 1.4502E-03
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL    2.5471E+00 +/- 2.5471E-04
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.  1.0967E+00 +/- 1.1394E-03
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.    9.2456E-01 +/- 8.4814E-04
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION   1.1862E-02 +/- 1.5198E-05
NEUTRAL CURRENT / QUARKONIC RADIATION       1.0164E-01 +/- 1.4252E-04
 *** INTEGRATED LUMINOSITY CORRESPONDING TO  70000000 EVENTS ***
     DLUMI=NEVENT/(SIGTOT*1E6)=   1.495E+01 FB^-1
```

Work in progress: CC with target polarization

Born: easy since $v_f^i = a_f^i = 1$, $D = \frac{G_F^2 M_W^4}{4\pi xyQ^2} \frac{Q^4}{\left(Q^2+M_W^2\right)^2}$

- $\frac{d^2\sigma^{W^\pm}}{dx\, dy} = D\left[F_2^{W^\pm} Y_+ \mp xF_3^{W^\pm} Y_-\right] + H\left[-2xg_5^{W^\pm} Y_+ \mp 2xg_1^{W^\pm} Y_-\right]$
- W^+ couples to down type quarks, W^- to up type quarks:

$$F_2^{W^+} \propto 2x(d+\overline{u}+\overline{c}+s), \qquad F_2^{W^-} \propto 2x(u+\overline{d}+\overline{s}+c),$$
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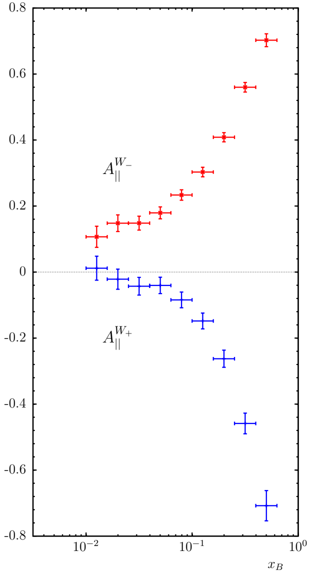
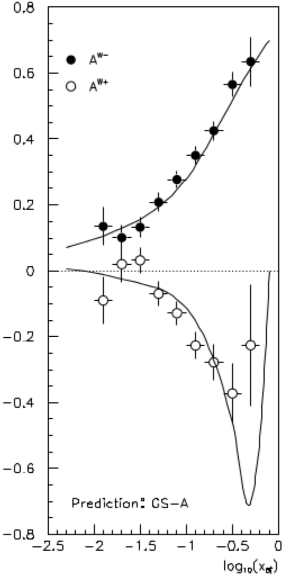
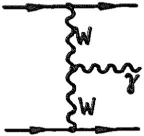
Comparison to Contreras,DeRoeck,Maul '97, pol. HERA, $Q^2 > 225\ GeV^2$





Work in progress: CC with target polarization

$\mathcal{O}(\alpha)$ corrections: analogy to NC not obviously clear due to appearance of diagrams with non-abelian $WW\gamma$ coupling [Spiesberger:Nucl.Ph.B349(1991)109-131]



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  $Q_{f'} = Q_f + Q_W, \ Q_W = Q_\ell$

⇒ Gauge invariant separation of the cross section:
$\sigma = Q_\ell^2 \mathcal{L} + Q_\ell Q_f \mathcal{I} + Q_f^2 \mathcal{H}$

- Divergences stemming from the initial lepton the final quark cancel with divergent terms in virtual corrections [KLN]
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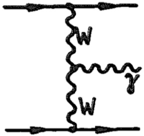

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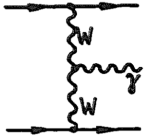

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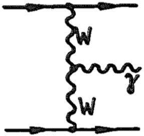

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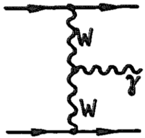

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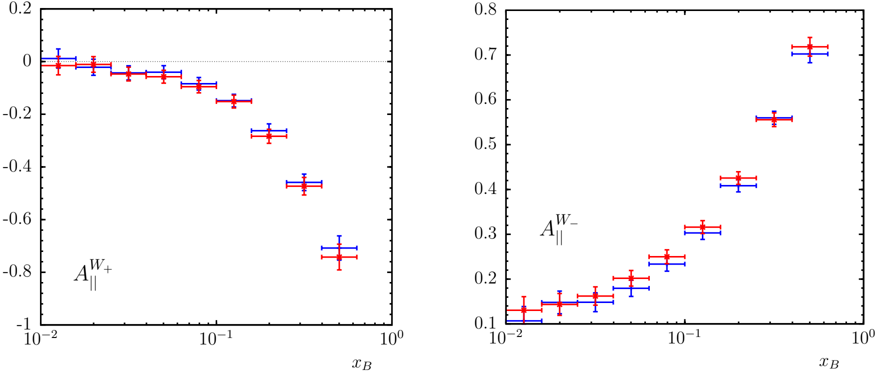
Effect of $\mathcal{O}(\alpha)$ corrections (red) on previously shown asymmetries (blue)



... further study and validation yet to come.

Overview

What I did

- working out of the structure of the cross section for deep inelastic scattering of longitudinal polarized leptons off longitudinal polarized hadrons with and without QED corrections:

$$\sigma_{\mathrm{B/rc}} = \sigma^{\mathrm{unpol}}_{\mathrm{B/rc}} + H\,\sigma^{\mathrm{pol}}_{\mathrm{B/rc}}$$

- implementation in DJANGOH's Fortran77 code:
  - extension by routine for access to spin dependent PDFs $\Delta q\left(x, Q^2\right)$ from various groups
  - construction of particular spin dependent contributions by means of available building blocks in the program
  - subjoining terms proportional to H and $\Delta q\left(x, Q^2\right)$ at appropriate locations in the code
- consistency check: generation of pseudo data and its processing with ROOT for comparison with theory and/or other publications and first predictions for eRHIC at the same time

$\Rightarrow$ new release of DJANGOH (vers. 4.6.10)

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More work to be done

- $\mathcal{O}(\alpha)$ corrections already $> 50\%$ in some regions of phase space $\rightarrow$ $\mathcal{O}(\alpha^2)$ corrections?
- weak and/or QCD corrections?
- parametrization of the cross section by means of structure functions instead of PDFs? $\rightarrow$ phase space regions with smaller Q^2
- consideration of lepton and hadron masses?
- transversal polarized particles?
- influence of nucleon polarization on hadronic final state (Fragmentation, parton cascades ...)?
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